N 62 14071

NASA TN D-1448

NASA TN-D-1448

TECHNICAL NOTE

D-1448

CORRECTION FOR ATMOSPHERIC REFRACTION AT THE NASA MINITRACK STATIONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON August 1962

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by

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SUMMARY

Each Minitrack Station of the NASA worldwide network is being calibrated every three to four months with the help of an aircraft. Since this is done optically, refraction corrections are applied to compensate for the bending of the light ray in the atmosphere. An analytical expression of the path of light in polar coordinates is developed in this paper by use of the Fermat Principle and the Method of Variational Calculus. With this equation an angular correction is derived which is to be applied for different heights of the calibration airplane and the Minitrack station. The equation derived is valid for zenith angles up to 75 degrees. This was done to make the expression valid not only for the Minitrack station calibration but also for the calibration of large dish antennas. The correction angle equation is limited to heights ≤ 30 km (16 n mi) and zenith angles ≤ 75 degrees; these limits are more than adequate for station calibration, and simplify the expressions considerably. It is also shown that this new equation for the correction angle differs significantly, for the stations in Quito ($h = 3.6$ km) and Johannesburg ($h = 1.6$ km), from the one previously used by NASA. This is because up to the present time only a rough approximation was used which did not take the elevation of the tracking station into account. The corrections given here should therefore be applied when data from these two stations dated prior to June 1961 are used. The equations derived here are used for all Minitrack station calibrations after that date.

ABSTRACT

All the Minitrack stations of the NASA worldwide network are being optically calibrated with the help of an aircraft.

To evaluate the data obtained from such tests, corrections must be applied to compensate for the refraction between airplane and ground station. In this paper an analytical expression is derived for the correction angle as a function of the atmosphere density (which is proportional to δ_0), its distribution κ, the zenith angle β_1^*, the height of the airplane h_2, and the height of the tracking station h_1.

The equation for the atmospheric correction developed in this paper has been used for the calibration of the world-wide Minitrack network since June 1961 and will also be used for the calibration of large NASA dish antennas.

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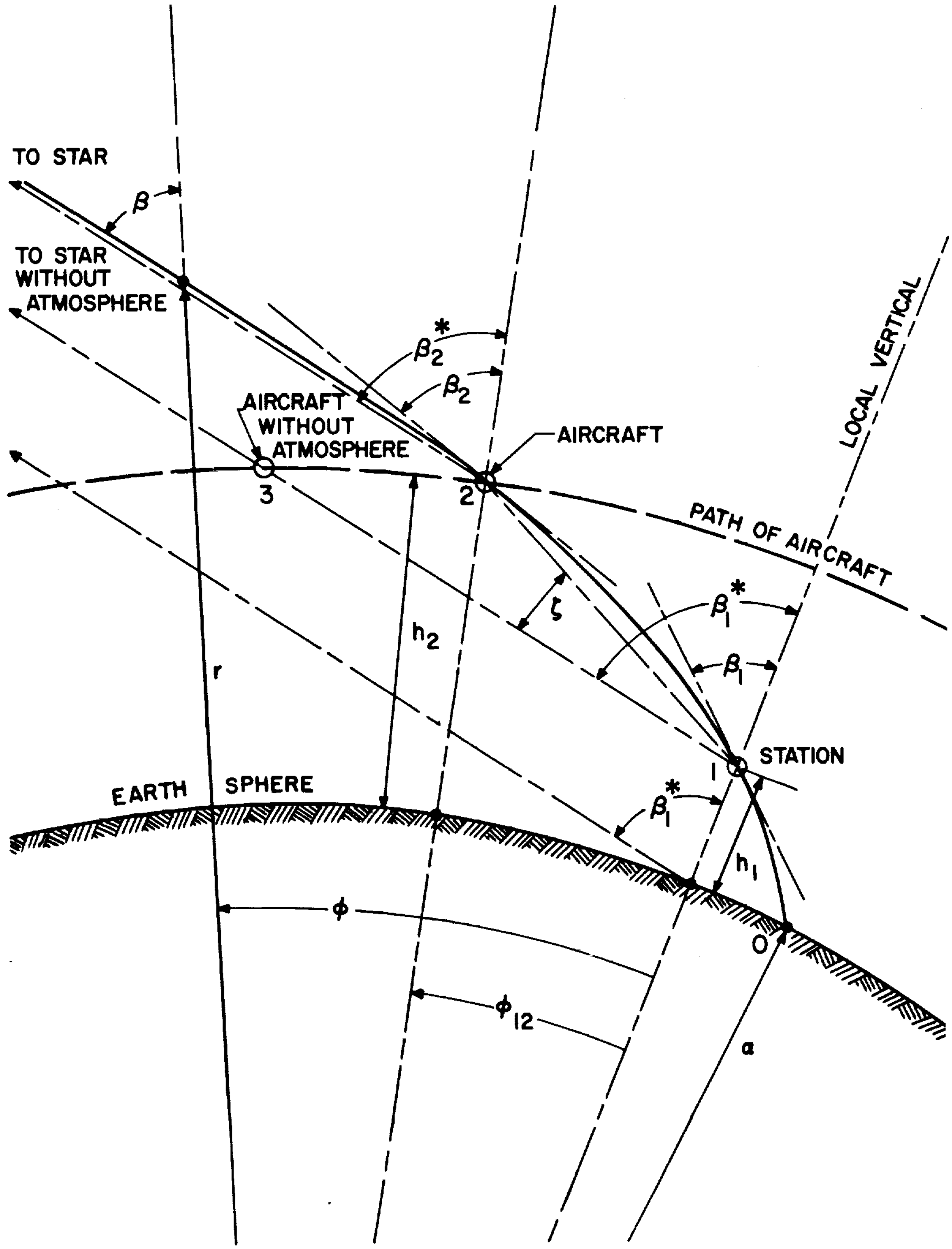

Figure 1—Fermat path of the light ray

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INTRODUCTION

Present day interferometer type tracking stations, such as the NASA Minitrack stations,† are very precise instruments which determine the unit position vector from the station to the satellite (Reference 1), i.e., actually measure two angles. The antennas used with these systems, are large fixed skeletal slot arrays separated by approximately two hundred meters and mounted on concrete piers. Thus, upon installation and every few months thereafter, these stations must be calibrated. For this purpose an airplane is equipped with a radio-frequency transmitter (136 Mc) and a flashing light synchronized in time with the ground station as described in Reference 1. Actual photographs are taken at the ground station of the flashing light against a star background, and from the image of stars and the flashing light in these photographs, a calibration of the station is made. In order to do this a correction must be made to compensate for the bending of the light ray from a distant star as well as from the calibration airplane.

THE FERMAT PATH OF THE LIGHT RAY

Before any calculations are made to determine the refraction angle correction ξ, (Figures 1 and 2) the equation of the path of the light, $\phi = \phi(r)$, has to be derived in a manner useful for evaluating ξ. It is well known that a light ray is bent in passing through an inhomogeneous medium. The Principle of Fermat (References 3-9) states that the light chooses that path between two points which involves the "shortest travel time." Mathematically expressed, this means that

$$T = \int_s \frac{ds}{v} = \text{minimum} \quad , \tag{1}$$

†Antofagasta, Chile; College, Alaska; Blossom Point, Maryland; East Grand Forks, Minnesota; Johannesburg, South Africa; Lima, Peru; St. John's Newfoundland; Woomera, Australia; Antigua Island, British West Indies; Quito, Ecuador; Santiago, Chile; Winkfield, England; Fort Myers, Florida; Goldstone Lake, California.

where T is the travel time of the light between the two points, S is the path length of the ray, v the velocity of the ray, and ds the line element along S. The solution of Equation 1 will result in the equation of the path of the light

$$\phi = \phi(r) . \qquad (2)$$

which will be treated here. Two values have to be introduced into Equation 1 before a formal solution can be obtained: the velocity

$$v = \frac{c}{n} \qquad (3)$$

of the light in the medium (where c is its velocity in a vacuum), and the index of refraction, n.

For convenience of calculation, the index of refraction n is not directly utilized; instead an expression

$$n = \left[1 + \delta_0 g(r)\right]^{1/2} \approx 1 + \frac{1}{2}\delta_0 g(r) \qquad (3a)$$

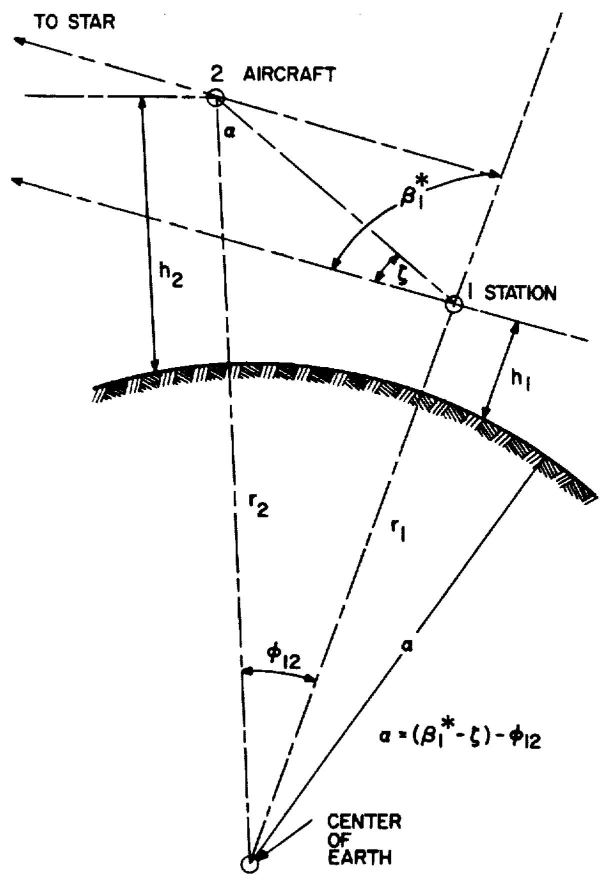

Figure 2—Angular relations

is used. The value $\delta_0 \approx 5.65 \times 10^{-4}$ (References 10, 11) depends, as Reference 10 shows† on pressure, temperature, wavelength of the light, and water vapor content of the atmosphere; and $g(r)$ is a normalized distribution function characterizing the density distribution with the height. This is, in general, an exponential function – or rather a near-exponential one (cf. References 12-16). Introducing Equations 3 and 3a and the line element in polar coordinates $ds = \sqrt{r^2\phi'^2 + 1}\, dr$ into Equation 1 results in

$$\frac{1}{c}\int_s \left[1 + \frac{1}{2}\delta_0 g(r)\right]\sqrt{r^2\phi'^2 + 1}\, dr = \text{minimum}, \qquad (1a)$$

where

$$\phi' = \frac{d\phi}{dr} \text{ (cf. Figure 1)}.$$

†On page 113 of Reference 10 the refraction is given in N-units: $(n-1)10^6 = N_0 = \frac{1}{2}\delta_0 \times 10^6$ relates the N-units with the quantity δ_0 used in the present paper.

We wish to determine the function F under the integral so that the minimum condition given by Equation 1a is fulfilled. Thus, F must satisfy the fundamental "Eulerian Differential Equation" (References 3-5):

$$[F]_{\phi} = F_{\phi} - \frac{d}{dr} F_{\phi'} = 0 , \tag{4}$$

giving the necessary condition for an extremum.† Now

$$F = \left(1 + \frac{1}{2}\delta_0 g\right)\sqrt{r^2\phi'^2 + 1} ; \tag{5}$$

consequently

$$F_{\phi} = \frac{\partial F}{\partial \phi} = 0$$

and, therefore,

$$\frac{d}{dr} F_{\phi'} = 0 . \tag{6}$$

Equation 6 can easily be solved:

$$F_{\phi'} = \frac{\partial F}{\partial \phi'} = \text{constant} . \tag{6a}$$

Differentiating Equation 5 with respect to ϕ' results (using Equation 6a) in:

$$\frac{\partial F}{\partial \phi'} = \left(1 + \frac{1}{2}\delta_0 g\right)\frac{r^2\phi'}{\sqrt{1 + r^2\phi'^2}} = \text{constant}$$

or, squaring,

$$\left(1 + \delta_0 g\right)\frac{r^4\phi'^2}{1 + r^2\phi'^2} = k^2 . \tag{7}$$

In polar coordinates the angle β (Figure 1) can easily be introduced by

$$\tan\beta = r\phi' ; \tag{8}$$

†One of the characteristic difficulties of the Calculus of Variations is that a meaningful formulation of a problem still can have no solution (see Reference 3, page 147). For a positive square root $F_{\phi'\phi'} > 0$, indicating a minimum.

therefore Equation 7 can be written as

$$\left(1 + \delta_0 g\right) \frac{r^2 \tan^2 \beta}{1 + \tan^2 \beta} = k^2 \tag{9}$$

or, equivalently,

$$\left(1 + \delta_0 g\right) r^2 \sin^2 \beta = k^2 . \tag{9a}$$

The constant k can now be determined from boundary conditions which can be chosen.

Since all star observations are corrected for atmospheric refraction (for zero atmosphere) the same condition is chosen here; that is, $\delta_0 = 0$ for a station of height h_1. Thus $\beta = \beta_1^*$ (cf. Figure 1) and $r = a + h_1 \approx r_1$. The constant k is then, from Equation 9a,

$$k = r_1 \sin \beta_1^* = \left(a + h_1\right) \sin \beta_1^* . \tag{10}$$

Equation 9a then becomes, if we take the square root and develop the first factor,

$$\left(1 + \frac{1}{2} \delta_0 g\right) \sin \beta = \sin \beta_1^* . \tag{9b}$$

With standard astronomical notation (Reference 11) for the normal atmospheric correction angle ρ, we have

$$\beta^* = \beta + \rho . \tag{11}$$

Inserting this into Equation 9b we obtain, for $\rho << 1$,

$$\rho = \frac{1}{2} \delta_0 g \tan \beta , \tag{12}$$

which represents the atmospheric corrections† to be applied to a star (Reference 11). From Equations 11 and 12 we obtain

$$\beta^* = \beta + \frac{1}{2} \delta_0 g(r) \tan \beta , \tag{12a}$$

giving the relation between the angles β^* and β for any height h above the ground. For the standard exponential atmosphere (References 10, 12, 13) Equation 12a reads

$$\beta^* = \beta + \frac{1}{2} \delta_0 e^{-\kappa h} \tan \beta , \tag{12b}$$

†With $\delta_0 = 5.65 \times 10^{-4}$ and $g = 1$ ($h = 0$), it is found that $\rho = 58.2 \tan \beta$. (Cf. Reference 10, p. 515, where for example $\rho \approx 60.3 \tan \beta$.)

where $h = (r - a)$ and $\kappa = 0.10501$ (Reference 13, p. 753) is a constant with the dimension km^{-1}. Thus β^* represents the angle, "without" atmosphere for any station height h and any zenith angle $\beta < 90°$ (Figure 1).

After this short excursion, let us return to the evaluation of Equation 7 — that is, to the determination of $\phi = \phi(r)$. From Equation 7 we obtain for ϕ'

$$\phi' = \frac{d\phi}{dr} = \frac{k}{r\sqrt{r^2 - k^2}\sqrt{1 + \delta_0 g\left(\frac{r^2}{r^2 - k^2}\right)}} \quad . \tag{13}$$

Now let us expand the second square root in Equation 13 to simplify the integration process. We shall make the abbreviation

$$\delta_0 g\left(\frac{r^2}{r^2 - k^2}\right) = \Delta \ , \tag{14}$$

where $\Delta \ll 1$ for the values $r_1 = a + h_1$ and $r_2 = a + h_2$, and $k = r_1 \sin\beta_1^*$ from Equation 10. Introducing practical maximum limits $h_1, h_2 \leq 30$ km, $\beta_1^* \leq 75°$ into the expression for Δ yields $\Delta_{max} \leq 8 \times 10^{-3}$.

The expansion of Equation 13 then results simply in

$$\phi' = \frac{k}{r\sqrt{r^2 - k^2}}\left(1 - \frac{1}{2}\Delta\right) \ . \tag{13a}$$

Integrating this gives, with Equation 14,

$$\phi_{12} = -\frac{1}{k} \arc \sin\left(\frac{k}{r}\right)\Bigg|_{r_1}^{r_2} - \frac{1}{2}\delta_0 k \int_{r_1}^{r_2} \frac{g(r)\,dr}{r^2\sqrt{\left[1 - \left(\frac{k}{r}\right)^2\right]^3}} \quad . \tag{15}$$

The integral in Equation 15 can be approximated by factoring out the function

$$f(r) = \frac{1}{r^2\sqrt{\left[1 - \left(\frac{k}{r}\right)^2\right]^3}} \tag{16}$$

and averaging it. That is,

$$I = \int_{r_1}^{r_2} f(r)\, g(r)\, dr \approx f(r)\Big|_{av} \int_{r_1}^{r_2} g(r)\, dr \tag{17}$$

or

$$I \approx f_{av} G .$$

This can be done since $f(r)$ differs but little between $r = r_1 = (a + h_1)$ and $r = r_2 = (a + h_2)$; that is, $f(r)$ is a slowly varying function within these boundaries. The maximum error* introduced by this simplification is approximately 5 percent for $\beta_1^* = 75°$, and is ≤ 1 percent for $\beta_1^* \leq 65°$. This justifies its use, whereby we obtain a closed and fairly simple expression for ϕ_{12}.

The ratio

$$\frac{f(r_2)}{f(r_1)} \approx \frac{1}{\sqrt{(1 + x)^3}} \tag{16a}$$

where

$$x = 2\left(\frac{h_2 - h_1}{a}\right) \tan^2 \beta_1^*$$

is, for the limits of h_1 h_2 and β_1^* stated before, approximately 0.90; and for $\beta = 60$ degrees, it is already approximately 0.97, quite close enough to unity to satisfy the condition stated above. The average value of $f(r)$ is then given by

$$f_{av} \approx \frac{1}{2}\left[f(r_2) + f(r_1)\right] . \tag{18}$$

Introducing Equation 10 and 16 into Equation 18, expanding the square root, and setting $r_1 \approx r_2 \approx a$ yields

$$f_{av} \approx \frac{1}{a^2 \cos^3 \beta_1^*}\left(1 - \frac{3}{4} x\right) . \tag{19}$$

*5% smaller than the "real" value.

From Equations 15, 17, and 19, the angle $\phi(r)$ can now be represented as

$$\phi_{12} = \beta_1^* - \arcsin\left(\frac{a + h_1}{a + h_2} \sin\beta_1^*\right) - \frac{1}{2}\delta_0 k f_{av} G . \tag{20}$$

Equation 20 represents, in essence, the equation of the "Fermat Path" $\phi = \phi(r)$ of the light ray entering the earth's atmosphere (Figure 1).

For most cases, the function $g(r)$ can be assumed to be an exponential one of the following form (References 10-14):

$$g(r) = e^{-\kappa(r-a)} , \tag{21}$$

where $\kappa = 0.10501\ \mathrm{km}^{-1}$ (Reference 13, p. 753). The integral G in Equation 17 is then given by

$$G = \frac{1}{\kappa}\left(e^{-\kappa h_1} - e^{-\kappa h_2}\right) \tag{22}$$

with

$$h_i = \left(r_i - a\right) , \quad i = 1,2 .$$

Equation 20 can be still further rewritten by using Equations 19 and 22, as follows:

$$\phi_{12} = \beta_1^* - \arcsin\left(\frac{r_2}{r_2} \sin\beta_1^*\right) - \epsilon , \tag{20b}$$

where

$$\epsilon = \frac{1}{2}\delta_0 \frac{1}{\kappa a} \tan\beta_1^*\left(1 + \tan^2\beta_1^*\right)\left(1 - \frac{3}{2}\Delta y \tan^2\beta_1^*\right) e^{-\kappa h_1}\left(1 - e^{-\kappa\Delta h}\right)$$

in which

$$\left.\begin{array}{l} \Delta y = \left(\dfrac{h_2 - h_1}{a}\right) \\ \text{and} \\ \Delta h = \left(h_2 - h_1\right) \end{array}\right\} \text{ for } \left\{\begin{array}{l} h_1,\ h_2 \le 30\ \text{km (90,000 ft)} \\ \text{and} \\ \beta_1^* \le 75^\circ . \end{array}\right.$$

For "no atmosphere," that is, for $\delta_0 = 0$, Equation 20b reduces to the equation of the straight line 1 → 3 → star (Figure 1), $\phi = \phi(r)$ in polar coordinates, as expected.

THE CORRECTION ANGLE

The star photographed and, for example, occulting the aircraft as in Figure 1, is "seen" from the station 1 at an angle β_1. In the star catalogs, on the other hand, the star's zenith angle β_1 is listed as the corrected angle β_1^*. In other words the atmosphere has been "removed".

Doing the same with the airplane's light images means that we must correct the airplane's position 2 (Figure 1) to that "without air," 3. The angle involved is the correction angle ξ. From the triangle in Figure 2 we obtain

$$r_2 \sin\left[\left(\beta_1^* - \phi_{12}\right) - \xi\right] = r_1 \sin\left[\pi - \left(\beta_1^* - \xi\right)\right] . \tag{21}$$

Since $\xi \ll 1$, Equation 21 can easily be solved for ξ:

$$\xi = \frac{\frac{r_1}{r_2} \sin\beta_1^* - \sin\left(\beta_1^* - \phi_{12}\right)}{\frac{r_1}{r_2} \cos\beta_1^* - \cos\left(\beta_1^* - \phi_{12}\right)} . \tag{22}$$

From Equation 20b the expression $\sin\left(\beta_1^* - \phi_{12}\right)$ can be introduced into Equation 22. With $\epsilon \ll 1$ we obtain, after expanding the trigonometric terms,

$$\xi = \frac{-\epsilon \cos\left(\phi_{12} - \beta_1^*\right)}{\frac{r_1}{r_2} \cos\beta_1^* - \cos\left(\beta_1^* - \phi_{12}\right)} . \tag{22a}$$

Expanding further the value

$$\frac{r_1}{r_2} = \frac{a + h_1}{a + h_2} \approx 1 - \left(\frac{h_2 - h_1}{a}\right) \approx 1 - \frac{\Delta h}{a} \tag{23}$$

and also developing the expression (from Equation 22a)

$$\frac{\cos\beta_1^*}{\cos\left(\beta_1^* - \phi_{12}\right)} = \frac{1}{1 + \phi_{12}\tan\beta_1^*} \approx \left(1 - \phi_{12}\tan\beta_1^*\right)$$

for $\phi_{12} \ll 1$, we obtain for ξ from Equation 22a:

$$\xi = \frac{a\epsilon}{\Delta h + a\phi_{12}\tan\beta_1^*} . \tag{22b}$$

The value of ϕ_{12} in Equation 22b can be introduced from Equation 20b, neglecting the pure refractive term due to the smallness of δ_0. Then, by developing the function

$$\arc\sin\left(\frac{r_1}{r_2}\sin\beta_1^*\right) = \arc\sin\left[\left(1 - \frac{\Delta h}{a}\right)\sin\beta_1^*\right]$$

in Equation 20b with $\Delta h\ a \ll 1$, we have the angle ϕ_{12} as

$$\phi_{12} \approx \frac{\Delta h}{a}\tan\beta_1^* \quad . \tag{20c}$$

Introducing Equation 20c into 22b yields:

$$\xi = \frac{a\epsilon}{\Delta h}\cos^2\beta_1^* \; . \tag{22c}$$

Finally, with Equations 20b and 22c, we can write for the airplane correction angle:

$$\xi = \frac{1}{2}\delta_0 \frac{1}{\kappa\Delta h}\tan\beta_1^* \left(1 - \frac{3}{2}\Delta y \tan^2\beta_1^*\right) e^{-\kappa h_1} \left(1 - e^{-\kappa\Delta h}\right) \quad , \tag{22d}$$

where

$$\left.\begin{array}{l} \Delta h = h_2 - h_1 \\ \text{and} \\ \Delta y = \dfrac{\Delta h}{a} \end{array}\right\} \quad \text{for} \quad \left\{\begin{array}{l} h_1, h_2 \le 30 \text{ km (90,000 ft.)} \\ \text{and} \\ \beta_1^* \le 75^\circ, \end{array}\right.$$

or, in seconds of arc using the equivalent value for $\delta_0/2$ from Reference 11 (this value should actually be calculated from the value $n_{t,p,f}$ given in Reference 10, p. 114):

$$\xi'' = 58.2 \frac{1}{\kappa\Delta h}\tan\beta_1^* \left(1 - \frac{3}{2}\Delta y \tan^2\beta_1^*\right) e^{-\kappa h_1} \left(1 - e^{-\kappa\Delta h}\right) \tag{22e}$$

Equations 22d and 22e represent the correction angle in the desired form

$$\xi = \xi\left(\delta_0, \kappa, \beta_1^*, h_1, h_2\right)$$

as stated at the beginning of this paper. The total error resulting from the approximations made in deriving the equation for the correction angle is approximately 3 percent for $\beta_1^* = 75^\circ$ and is negligible at angles $\beta \le 65^\circ$.

Equation 22 does not, of course, present the whole picture, since the values δ_0 and κ vary in nature $(\Delta\delta_0, \Delta\kappa)$ as is shown, for example in References 15 and 17. It is therefore appropriate to calculate the variations σ_ξ of ξ resulting from the uncertainties in the values δ_0 and κ. Assuming that these two quantities are not correlated, the error can be given by using the simple expression for error propagation:

$$\sigma_\xi^2 = \left(\frac{\partial \xi}{\partial \delta_0} \Delta\delta_0\right)^2 + \left(\frac{\partial \xi}{\partial \kappa} \Delta\kappa\right)^2 \quad . \tag{23}$$

Introducing Equation 22d into 23 we obtain after some manipulation:

$$\sigma_\xi = \pm \xi \left[\left(\frac{\Delta\delta_0}{\delta_0}\right)^2 + 4\left(\frac{\Delta\kappa}{\kappa}\right)^2\right]^{1/2} \tag{23a}$$

These errors, based on measured values of $\Delta\delta_0/\delta_0 \approx 10^{-1}$ (see Reference 17) and $\Delta\kappa/\kappa \approx 4 \times 10^{-2}$, are not shown in Figures 3 and 4. (Also see, for instance, Reference 15, p. 753, where $\kappa = 0.1057$; and Reference 10 where $\kappa = 0.1090$ is calculated from a table given on p. 113 for a 10 km height.) Using these values, we obtain approximately

$$\sigma_\xi \approx \frac{\xi}{10} \tag{23b}$$

as a maximum spread (winter to summer).

If the density variation and therefore the variation in δ_0 can be measured, the value of σ_ξ becomes smaller accordingly.

Figures 3 and 4 show the correction angles which are applied for the Minitrack station calibration. For the Johannesburg and Quito stations the correction angle deviates largely from the approximate equation used previously, which did not properly take the height of the tracking station into account.

CONCLUSION

An improved equation has been derived for the correction angle to be applied where an aircraft is used for calibration of the NASA Minitrack stations. This correction has been in use for calibration of these stations since June 1961. Figures 3 and 4 show the difference between the previously used correction for Johannesburg and Quito – which did not include the height of the observation station – and that derived in this paper. Data from these two stations published and used prior to June 1961 should be corrected accordingly.

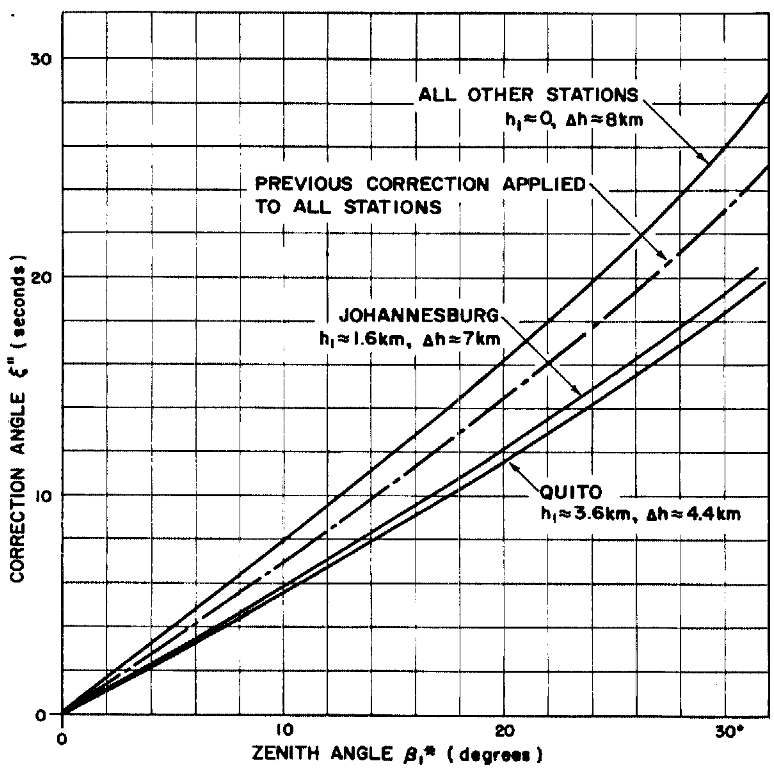

Figure 3—Correction angle ξ'' as a function of zenith angle β_1^* for $\beta_1^* \leq 32°$

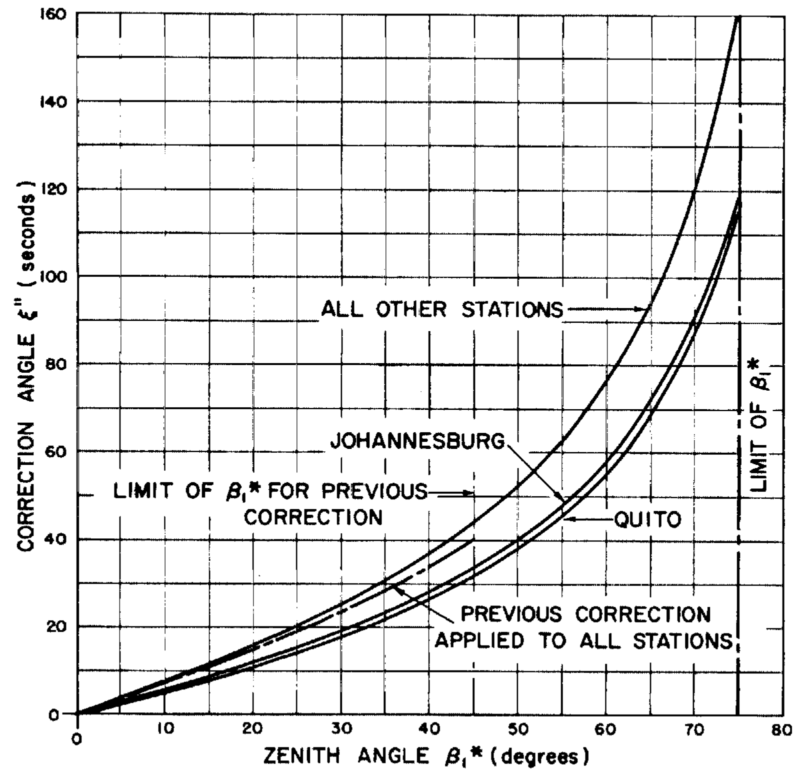

Figure 4—Correction angle ξ'' as a function of zenith angle β_1^* for $\beta_1^* \leq 75°$

ACKNOWLEDGMENTS

The author wishes to acknowledge the helpful discussions and suggestions of Mr. E. Habib and Mr. J. Berbert. In particular the author wishes to thank Mr. A. Berndt for carefully proofreading the manuscript and correcting some of the derived expressions, and Mr. T. Jones for the numerical evaluations.

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NASA TN D-1448
National Aeronautics and Space Administration.
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I. Vonbun, F. O.
II. NASA TN D-1448

(Initial NASA distribution: 18, Communications and tracking installations, ground; 29, Navigation and navigation equipment; 33, Physics, theoretical; 45, Research and development facilities; 49, Simulators and computers.)

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